BIFACIAL PV SYSTEMS: MAIN FACTORS AFFECTING THE ENERGY GAIN DUE TO REAR SIDE CONTRIBUTION

Introduction.

The beauty of bifacial PV systems is in the collecting of additional light energy by the modules back providing an increased energy generation. After first space application of bifacial solar cells in 1970-ies to supply additional energy, using Earth Albedo [1,2] it was demonstrated that such cells are very attractive for extra energy generation also on earth.

Fig. 1. Terrestrial bifacial PV system

A module placed outdoor as in Figure 1 will generate energy according to irradiation that incident on its front and back simultaneously. This irradiation is generally composed of direct (plus some diffused) sunlight on the front and reflected diffused (and sometimes direct) light on the back.

Whereas energy generation by regular mono-facial module is well studied and foreseeable, the forecast experience of energy production by bifacial module is very limited. Among factors affecting the back energy generation are:

1. Illumination conditions dependent on geographical, climatic and time factors:
   - Sun elevation
   - Diffused/global radiation
2. Module and system design parameters:
   - Module “bifacial factor” (back/front short currents ratio)
   - Module inclination
   - Distance between rows
   - Stand-alone/field system
   - Module elevation above underlying surface
   - Distance between modules in the row
   - Albedo of underlying surface

All the above factors effect mostly on the back irradiation and therefore on the added energy generation, or energy gain, $EG$. The energy yield of bifacial module $Eb$, with subtraction of energy yield of mono-facial module $Em$, at the same conditions will result in the energy gain. To exclude an effect of possible difference in the front powers of both modules the yield should be normalized relative to nominal front power of each module. Therefore the correct definition of the energy gain is:

$$EG = \underbrace{\frac{Eb}{P_{fb}}} - \underbrace{\frac{Em}{P_{fm}}}$$

Where $P_{fb}$ – power at standard conditions of front illuminated bifacial module $P_{fm}$ - power at standard conditions of illuminated mono-facial module.
Energy gain is not constant for a given module and depends on above factors. The range of possible EG values characterizes the energy production ability of the module and system. In parallel to EG additional factors can be used for characterization of energy production capability of a bifacial module. They are equivalent efficiency and equivalent nominal power.

Equivalent efficiency of a bifacial cell or module is the efficiency of a mono-facial cell or module providing the same energy as the bifacial one. Therefore the equivalent efficiency of a bifacial cell or module can be expressed by the following:

\[ \eta_{\text{b\,equ}} = \eta_{\text{fm}} \cdot (1 + \text{EG}) \]

In the same way the equivalent power of a bifacial cell or module will be expressed by:

\[ P_{\text{b\,equ}} = P_{\text{fm}} \cdot (1 + \text{EG}) \]

**Module back irradiance characteristics**

Rear irradiance non uniformity is one of the important factors which should be taken in the consideration when designing or evaluating bifacial system energy generation. Examples of the back module irradiance distribution are shown in Fig.2 [3]. Measurements were made in Jerusalem (31° North latitude) on May 29th at noon. Irradiance on horizontal surface 1006 W/m²; diffuse to global radiation ratio 0.11; underlying surface albedo 50 %; Tilt of module: 30° from horizontal.

Fig. 2. Non uniformity of back side irradiance for a 30° tilted module as function of module elevation

Left diagram: 8 cm and Right diagram: 58 cm, over ground.

As can be seen, the back irradiance is non uniform, and the non-uniformity depends dramatically on the module elevation. The irradiance values are in the range 66 - 328 W/m², i.e. varying ~5 times, in the case of lower module elevation, and in the range 360 -390 W/m² (varying ~ 10 % only) in the case of highest elevation. Fig. 3 summarizes the changes of back module irradiance, i.e. non-uniformity, vs. module elevation. The curves reflect the range between min and max back irradiance for the case where the module is fixed with 30° tilt and mounted in a field where the distance between rows (in S-N direction) is 150 cm and between separate modules (in E-W direction) 20 cm.
Fig. 3. Illumination non uniformity characterized by max and min back irradiance on the module as function of module elevation (albedo of the underlying surface is 50\%).

The reflectivity of the underlying surface has the dominating effect on the back irradiance. Minimal back irradiance increases nearly proportionally to albedo of the underlying surface, when diffusion component of solar irradiation is small. This can be seen in Fig. 4 for two albedo cases: 0.25 (blue curve) and 0.55 (red curve). Minimal back irradiance will be used for the irradiance gain evaluation necessary for the power gain determination.

Uniformity of back irradiance is significantly better under conditions of dominating diffuse radiation. The same Fig. 4 illustrates comparative data on irradiance of rear panel side for different weather conditions. For the cloudy day the following illumination conditions that were measured are: global irradiance \(\sim 190 \text{ W/m}^2\), diffuse/global ratio 0.98. In the case of cloudy weather (dominating diffuse radiation) uniformity of irradiance is significantly better even at low elevations (yellow curve). Comparison between this curve and the red one shows also that the ratio of back to front irradiance is higher in the case of diffuse sun illumination (43%) than in the case of nice direct illumination (\(\sim 24\%\)).

Fig. 4. Irradiance gain as function of weather, albedo and panel elevation

__Electrical contribution of the module back__
The electrical measurements of module back only (with front covered by non-transparent sheet) and of module with both sides illuminated (front by sun, back by scattered light) shows that back contribution is limited by lowest irradiated area. This restriction of back contribution in the module maximal power $P_{\text{max}}$ is illustrated by Fig. 5 for the module, which bifaciality factor is 71%. The gain increases with elevation raise is determined largely by irradiance distribution improvement and in the less extent by increase of absolute irradiance of the back (see Fig. 3).

Fig. 5. Max power gain (limited by minimal back irradiance) vs. elevation for a bifacial module at fixed tilt of 30 degree (bifacial factor is 71%).

**Outdoor monitoring**

Comparative outdoor measurements of bifacial and mono-facial modules and systems were undertaken in several geographical places [3-6].

**One of the monitoring sites** is Jerusalem (North altitude 31°47'). Fig. 6 represents the view of the rooftop test station. Comparative measurements of bifacial and mono-facial modules were made when modules of both types were mounted inside the "field" of several module rows. The modules were oriented at a fixed position south at 30° to the horizon. The distance between rows (in S-N direction) and between separate modules (in E-W direction) was 150 and 20 cm, respectively. Elevation of the module lower edge was 70 cm.

Fig. 6. Rooftop test field in Jerusalem
The summary of comparative monitoring of bifacial and mono-facial modules is shown in Fig. 7 as monthly energy generation gain [4, 5]. The bifacility factor is 71%, albedo of underlying surface is 50%. The generated energy gain is normalized by nominal module front power at standard conditions. The measured bifacial gain is varying depending on year time in the range 9–20% with annual gain above ~15%. During this experiment, the energy production was determined by integrating the DC power of the modules measured every 3 min.

![Fig. 7. Monthly energy gain of a bifacial vs. a monofacial module](image)

The gain for a stand-alone bifacial module for several months is also shown in the Figure. As can be seen, the stand-alone bifacial module provides ~22 to ~30% energy gain (an additional ~3 to ~13% comparing to in-field module energy gain). It should be mentioned, that the maximal power generated by bifacial module in stand alone condition is the value which should be used as an analog of the mono facial module power at standard conditions for the safe module and system designs.

Some details of comparative monitoring of energy generation by mono-facial and bifacial modules is presented as time-of-day dependence. An example of such dependence for a sunny day is presented in Fig. 8. [4, 5]. The increased gain can be seen for the morning and evening hours, when portion of scattered radiation is larger. (Due to the site topography causing shading of the sun in the evening, when it is below ~20° above the horizon, the contribution of the back of a bifacial module is decreased in the afternoon). In the morning the direct sun rays hit the back (in the time frame between the spring and the autumn equinoxes). Because of morning and evening effects, the daily gain is significantly higher than during the middle of the day.
The same type of measurements for a day with prevailing diffused radiation (Fig. 9) shows a significant increase in gain when diffused radiation dominates: ~38% when diffused/global radiation ratio is 88% compared to ~16% when 89% of radiation is direct sun radiation.

Some additional improvement in AC energy generation can be seen due to significant increase (up to 2 times or even more) of DC energy at the inverter input at morning and at evening. Increased DC energy allows to shift the inverter mode to higher efficiency region and sometimes from below to higher of threshold working level.

Another monitored system included in the current discussion is located in Geilenkirchen, Germany, latitude ~51° North (Pohlen test site, monitored by Fraunhofer ISE) [5]. The flat roof top systems with separate inverters were composed by 6 bifacial and 7 mono-facial modules. The modules installation parameters were: height 0.3 m, tilt 15°, NS row distance 2.5 m. Albedo value of 78% was measured at the beginning of monitoring and ~55% after ~1 year.

According to monitoring data, the energy generated due to back contribution exceeds 20% every month. Jump in bifacial gain during Jan-Feb illustrates additional advantage of bifacial modules. After
snowfall, the contributions of the backside of the bifacial modules increase due to high snow reflection. In the same time, the front side covered by the snow generates less energy, and gain value increases significantly. A 23% annual bifacial gain is evaluated. Equivalent power of each of the bifacial module (i.e. power of mono-facial module able to generate the same energy as bifacial one) is 307.5 W, while its front power is 250 W. Equivalent efficiency of the cells is 22.75 %, while their front efficiency is 18.5 %.

Simulation of the system gain

Examples of bifacial system performance simulation for different field design parameters can be seen in Fig. 12 (the place of the field is Germany, Hannover, Latitude: 52° 22' ) [6]. Panel tilt is equal to the altitude of the given place. This panel position provides the maximal energy collected by the panel front. The basic bifacial modul choosed fo calculations assumed to be build using solar cells with front efficiency 20 %. Bifaciality factor of the module is 90 %.

The gain is shown as functions of distance from the panel lower edge to the ground (panel height). The calculations are prepared for three types of system: packed min, i.e. minimal NS distance providing no shading at 21st December noon, spaced min, i.e. minimal NS distance x 1.5; single panel. Three albedo values were chosen in the range of typical coats: tarred roof, dry soil (25 %), white agricultural canvas, polluted white roof coats (50 %) and cool white roof coat, snow (80 %).

Fig. 11. Monthly energy gain of a bifacial vs. a monofacial PV system.

Fig. 12. Examples of forecast calculation of bifacial PV system for different design parameters.
It can be seen that two design parameters are most influential on the gain: panel elevation and albedo of underlying surface. Increasing the elevation of panel above the underlying surface results in multiplication of the gain. Positive effect of panel height increase is starting to saturate at 0.4 – 0.5 m. Increase of the gain due to higher albedo is obvious – the gain is ~ directly proportional to the albedo. No dramatical effect of row spacing of the field. Therefore NS distance between the rows can be selected without taking the gain in the consideration.

Even using bifacial cell of moderate front efficiency as a building element in PV system is equivalent to creation of monofacial systems based on the cells of 26 -28 % efficiency, what is close or above the achievable maximum.

Conclusions
Simultaneous monitoring of I-V characteristics of mono- and bifacial modules and systems demonstrates superiorities of bifacial over mono-facial type of PV energy generators.

Yearly energy gain of an in-field bifacial vs. a mono-facial module in low latitude position (Israel) with an underlying surface albedo ~0.50 and bifaciality factor of the module 71 % is above 16 %. In higher latitudes position (Germany) the energy gain is above 23 %.

These values can be easily increased above 23 % and 30 % respectively by optimization of PV field design and increasing the bifacial factor to 90 %. This was shown both by outdoor monitoring and simulation.

According to calculations, an equivalent efficiency of bifacial solar cells with front efficiency 20 % imbedded in the modules of bifacial systems are in the range 26 -28 %. The values of energy generation and equivalent efficiencies, which can be realized using modern bifacial cells, are far above the levels of the best regular mono facial silicon cells.

References
Definition and formulation of “ENERGY GAIN”

Determination of module starting parameters
- bifaciality factor
- maximal module current at solar illumination

Design factors of PV system
- Distance between modules, inside the rows and between the rows.
- Module’s elevation
- Albedo of underlying surface.

Climatically/geographically dependent factors
- Diffuse to global radiation ratio
- Seasonal and time-of-day sun position and module’s tilt.

The description will be illustrated by experimental outdoor data:
- Effect of illumination non uniformity;
- Monitoring of daytime energy generation by regular and bifacial modules;
- Monthly energy gain of a bifacial vs. a mono- facial module for Jerusalem (31ø latitude)
- Monthly energy gain of a bifacial vs. a mono- facial module for Geilenkirchen, Germany (Latitude 51ø)

I hope it helps and we can start to write soon the paper according to your remarks.